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# APPROACHES TO NUMERICAL MODELING IN THE DEVELOPMENT PROCESS OF COMPLEX STRUCTURES FOR FUSION DEVICES

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# Outline

Introduction

Approaches

- Simplified beam/shell approach
  *(Busbar system for W7-X)*
- Multifield analysis including electromagnetic transients
  *(ITER diagnostic port plug)*
- Engineering material model for serration effect
  *(W7-X magnet system)*

Conclusions

# Introduction

Components in fusion experiments subject to multiple loads of different nature together with lack of space for supports.

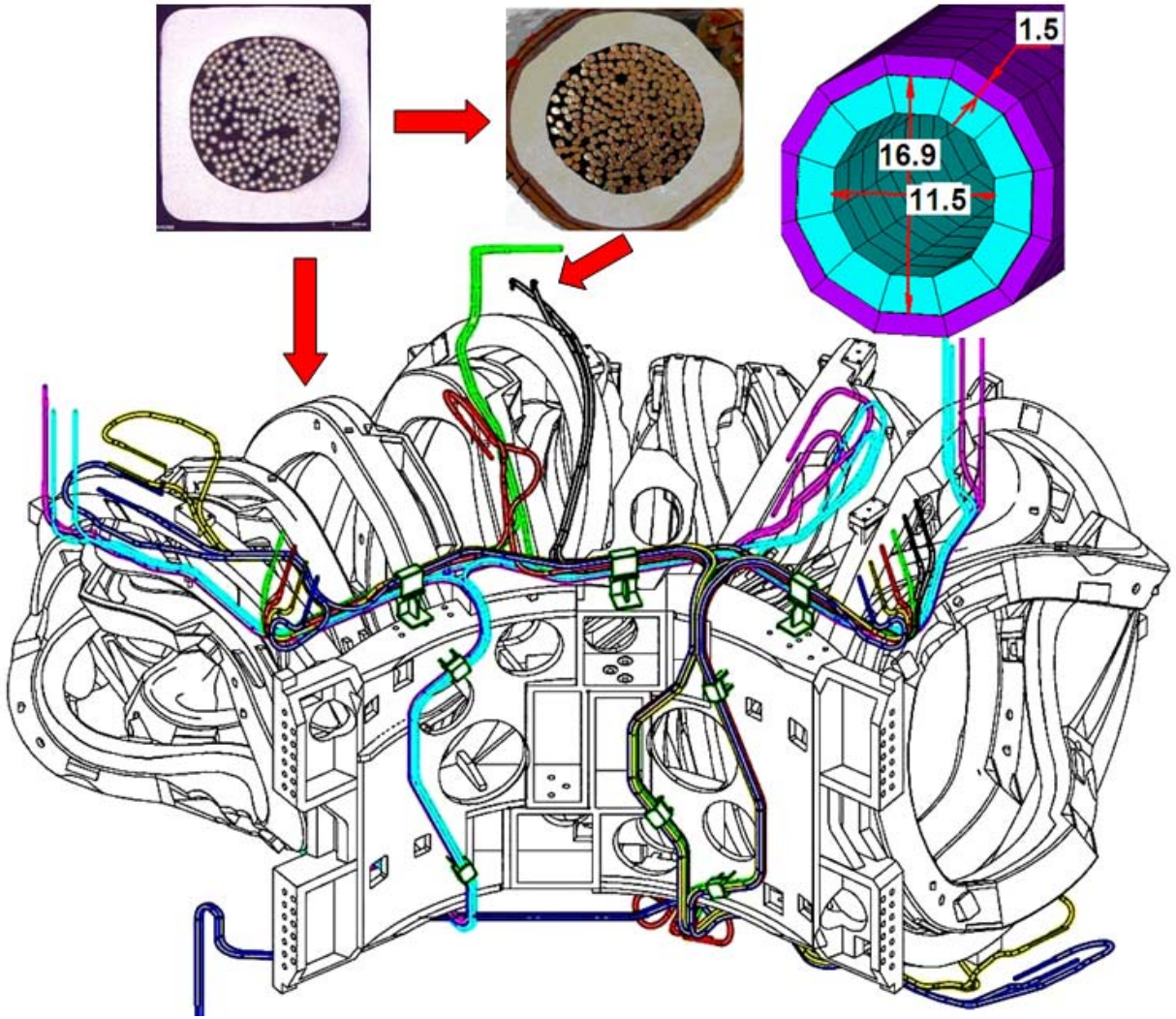
Design validation according to applicable codes and standards comprises numerous simulations.

Getting structural response of a single finite element model to combined loading from different sources, including electromagnetic transients is challenging.

Multifield finite element analysis is determined by the iterative nature of the design process.

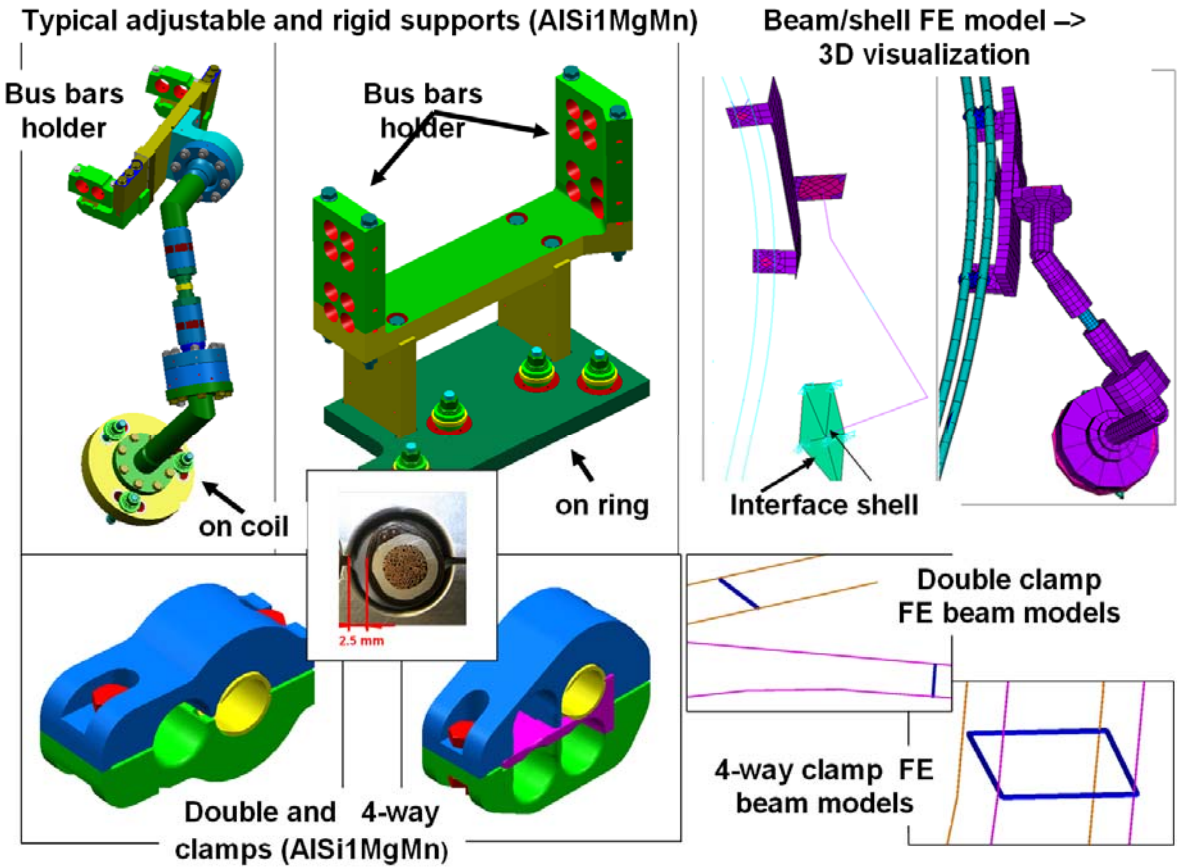
Customized analysis strategies required.

# Simplified Beam/shell Approach
# Busbar System for W7-X – Problem Description




- Bus to connect all identical coils
- Lorentz force
- Relative movement of coils and supports under magnet load
- Difference in temperature (contraction) of neighboring busbars at cool down
- Adjustability for tolerances
- Lack of space for supports
- Long and flexible busbars (121) with numerous supports (~400) and clamps (~400)
- Direct modeling for analysis from CAD seems impossible

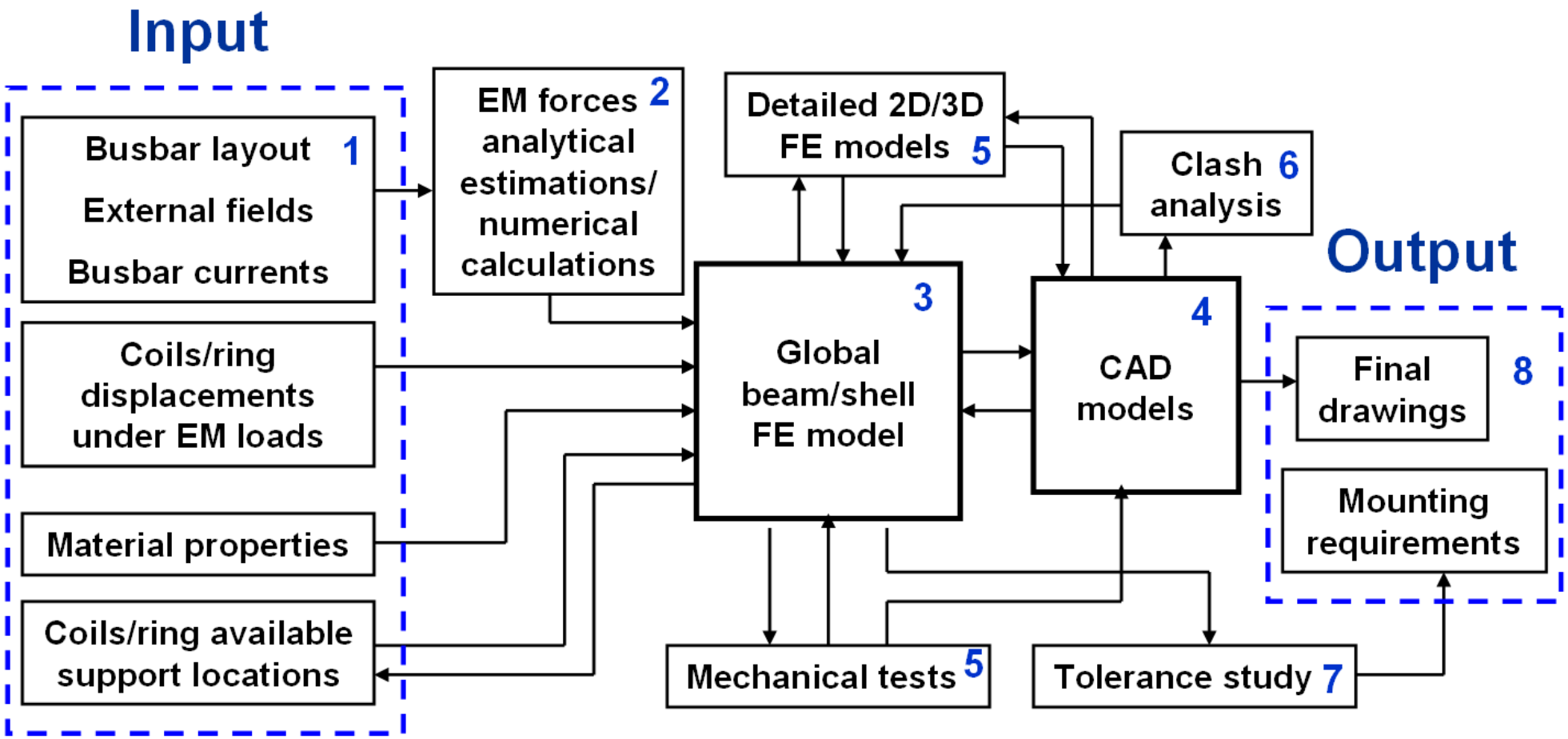
# Simplified Beam/shell Approach
# Busbar System for W7-X – Beam/Shell Elements




- Allows busbar assembly in tight space
- Keeps stresses in busbars below allowable values
- Limits busbar movements to avoid collisions

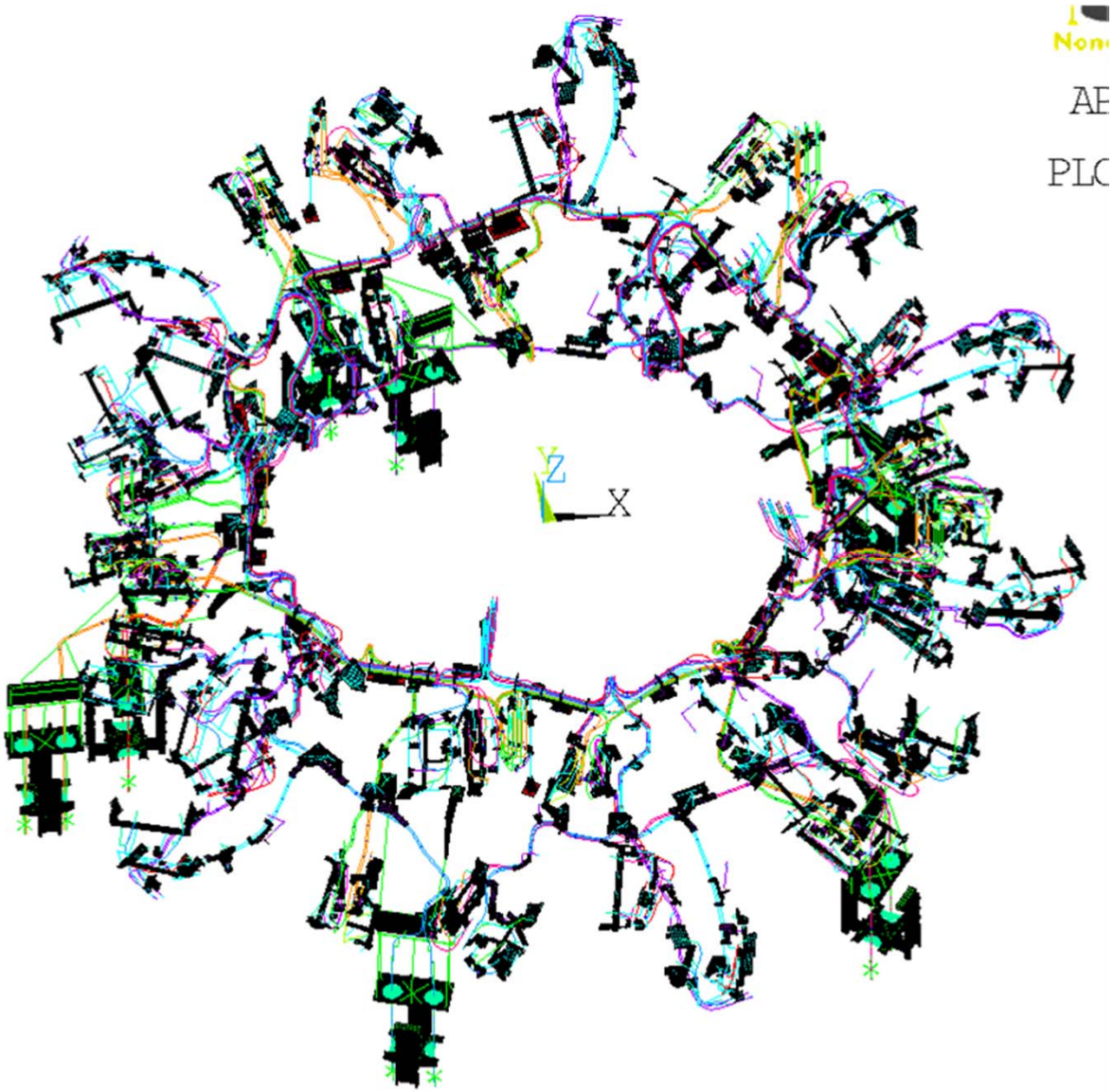
- 3D beam elements representing lines in space with arbitrary cross section for stiffness and stresses
- 3D shell elements representing surfaces in space with varying thickness
- Both directly supply main stress components required by design criteria
- 3D effects, like stress concentration, not regarded

# Simplified Beam/shell Approach Busbar System for W7-X – Design and Analysis Workflow



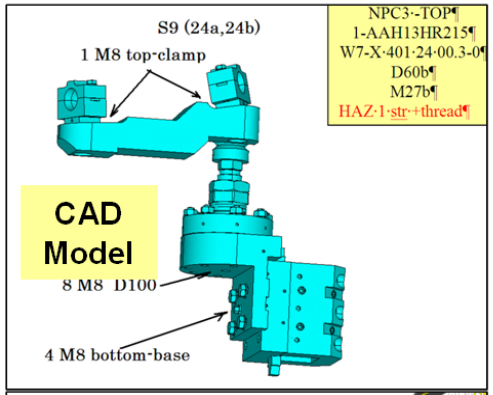

Multiple iterations of *design - global / local analysis – test*

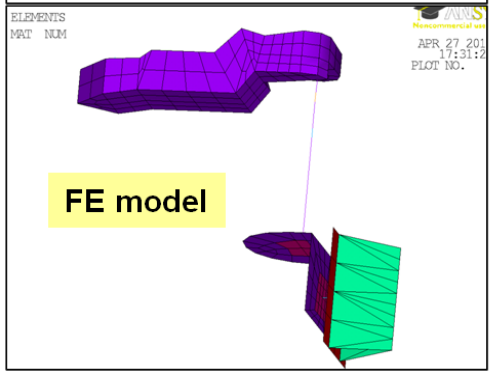
# Simplified Beam/shell Approach
# Busbar System for W7-X – Global FE Model

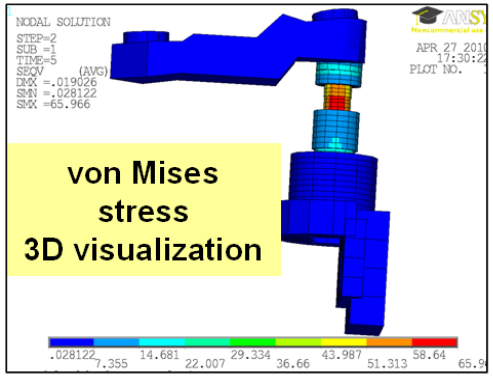



- Includes all busbars and supports
- Reflects main system features like stiffness and interaction
- Simple and flexible to changes
- Main stress components from 3D visualization of beam/shell elements
- Forces and moments for system analysis and changes, mechanical tests, and detailed 3D FE studies
- Runtime 30 min on office PC

# Simplified Beam/shell Approach
# Busbar System for W7-X – Detailed Analysis




## Loads and stresses in critical bolts

Support Bolts | Module 1 | 19.11.2009 | runst_12

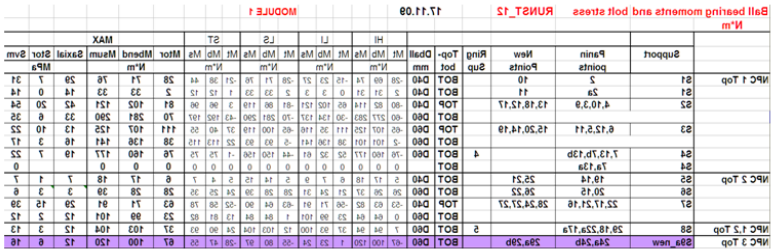
| Coil | Support | Panin points | New points | Comment | N bolts | M | MAX S MPa | MAX F kN | MAX Mtor N m | MAX Mbend N m |
|---|---|---|---|---|---|---|---|---|---|---|
| NPC 1 Top | S1 | 2 | 10 | top-clamp | 1 | M 8 | 49 | 1.6 | 1 | 14 |
| | | 8 | 16 | top-clamp | 1 | M 8 | 133 | 4.4 | 2 | 35 |
| | | | | bottom | 2 | M 6 | 201 | 3.6 | 5 | 145 |
| | S3 | 6,12,5,11 | 15,20,14,19 | top | 4 | M 8 | 53 | 1.8 | 64 | 131 |
| | | | | base | 3 | M 12 | 30 | 2.3 | 116 | 239 |
| | S4 | 7,13,7b,13b | | base | 4 | M 12 | 17 | 1.3 | 76 | 160 |
| | | | | top | 1 | M 12 | 94 | 7.2 | 76 | 127 |
| NPC 2 Top | S5 | 19,14 | 25,21 | middle | 3 | M 6 | 28 | 0.5 | 12 | 21 |
| | S6 | 20,15 | 26,22 | base | 3 | M 12 | 3 | 0.3 | 28 | 28 |
| | S7 | 22,17,21,16 | 28,24,27,23 | base | 3 | M 12 | 12 | 0.9 | 23 | 99 |
| NPC 2,3 Top | S8 | 29,18,22a,17a | | base | 4 | M 12 | 29 | 2.2 | 48 | 160 |
| | | | | top | 1 | M 12 | 61 | 4.7 | 37 | 85 |
| NPC 3 Top | S9a_new | 24a,24b | 29a,29b | bottom-base | 4 | M 8 | 21 | 0.7 | 139 | 82 |
| | | | | BB D60 | 8 | M 8 | 13 | 0.4 | 67 | 114 |
| | | | | top-clamp | 1 | M 8 | 24 | 0.8 | 2 | 10 |
| | | | | top-clamp | 1 | M 8 | 21 | 0.7 | 0 | 7 |

## Loads and stresses in aluminum thread

SUPPORT THREAD MOMENTS & stresses
Moments - N*m, stress - MPa | RUNST_12 | 17.11.09 | MODULE 1

| ******** Supports top HALF **** | Bolts | HI Mtor | HI Mben | HI Stor | HI Sben | HI Svm | LI Mtor | LI Mben | LI Stor | LI Sben | LI Svm | LS Mtor | LS Mben | LS Stor | LS Sben | LS Svm | ST Mtor | ST Mben | ST Stor | ST Sben | ST Svm | MAX Mtors N* m | MAX Mbend N* m | MAX Stor MPa | MAX Sbend MPa | MAX Svm MPa | Comments | HAZ thread |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N*.m | | | MPa | | N*.m | | | MPa | | N*.m | | | MPa | | N*.m | | | MPa | | | | | | | | |
| S1_bot_p2 | M24. | 28 | 42 | 17 | 51 | 59 | 15 | 13 | 9 | 16 | 22 | 28 | 43 | 17 | 52 | 60 | 21 | 23 | 13 | 28 | 36 | 28 | 43 | 17 | 52 | 60 | | |
| S1_bot_p2a | M20. | 2 | 16 | 2 | 33 | 34 | 0 | 2 | 0 | 5 | 5 | 2 | 17 | 3 | 35 | 36 | 1 | 6 | 1 | 12 | 12 | 2 | 17 | 3 | 35 | 36 | | |
| S2_bot_p4,10,3,9 | M32. | 72 | 207 | 14 | 78 | 82 | 35 | 144 | 7 | 54 | 56 | 83 | 210 | 16 | 79 | 84 | 51 | 166 | 10 | 63 | 65 | 83 | 210 | 16 | 79 | 84 | | |
| S3_bot_p6,12,5,11 | M27. | 2 | 46 | 1 | 37 | 37 | 38 | 123 | 15 | 99 | 103 | 5 | 44 | 2 | 35 | 35 | 22 | 81 | 9 | 65 | 67 | 38 | 123 | 15 | 99 | 103 | | |
| S4_bot_p7,13,7b,13b | M27. | 76 | 126 | 31 | 102 | 115 | 52 | 37 | 21 | 30 | 47 | 44 | 126 | 18 | 101 | 106 | 1 | 64 | 0 | 52 | 52 | 76 | 126 | 31 | 102 | 115 | | |
| S5_bot_p19,14 | M20. | 5 | 4 | 5 | 9 | 13 | 6 | 5 | 6 | 10 | 14 | 5 | 2 | 6 | 5 | 11 | 5 | 1 | 6 | 3 | 10 | 6 | 5 | 6 | 10 | 14 | | |
| S6_bot_p20,15 | M27. | 26 | 6 | 11 | 5 | 19 | 21 | 19 | 8 | 16 | 21 | 28 | 8 | 11 | 6 | 20 | 24 | 13 | 10 | 11 | 20 | 28 | 19 | 11 | 16 | 21 | | |
| S7_bot_p22,17,21,16 | M27. | 1 | 58 | 0 | 46 | 46 | 20 | 79 | 8 | 63 | 65 | 1 | 70 | 0 | 56 | 56 | 10 | 64 | 4 | 51 | 52 | 20 | 79 | 8 | 63 | 65 | | yes |
| S8_top_p29,18,22a,17a | M27. | 7 | 86 | 3 | 69 | 69 | 37 | 68 | 15 | 47 | 53 | 12 | 91 | 5 | 73 | 73 | 24 | 70 | 10 | 56 | 58 | 37 | 91 | 15 | 73 | 73 | | |
| S9_top_p24a,24b | M27. | 67 | 57 | 27 | 46 | 66 | 1 | 23 | 0 | 18 | 18 | 55 | 45 | 22 | 36 | 53 | 28 | 28 | 11 | 22 | 30 | 67 | 57 | 27 | 46 | 66 | | yes |

## Moments taken by spherical hinge



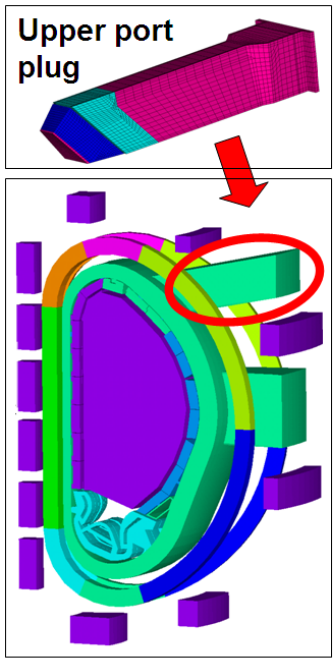

## Loads and stresses in aluminum weld

SUPPORT Alu welds MOMENTS & stresses
Moments - N*m, stress - MPa | RUNST_12 | 17.11.09 | MODULE 1

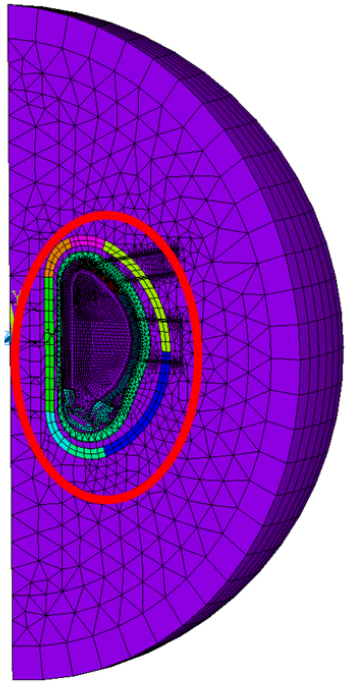
| ******** Supports TOP HALF **** | MAT | HI Mtor | HI Mben | HI Stor | HI Sben | HI Svm | LI Mtor | LI Mben | LI Stor | LI Sben | LI Svm | LS Mtor | LS Mben | LS Stor | LS Sben | LS Svm | ST Mtor | ST Mben | ST Stor | ST Sben | ST Svm | MAX Mtors N* m | MAX Mbend N* m | MAX Stor MPa | MAX Sbend MPa | MAX Svm MPa | Mbend for test N *m |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | N*.m | | | MPa | | N*.m | | | MPa | | N*.m | | | MPa | | N*.m | | | MPa | | | | | | | |
| S3_top | 117 | 2 | 61 | 0 | 15 | 15 | 38 | 111 | 5 | 28 | 29 | 5 | 61 | 1 | 15 | 15 | 22 | 42 | 3 | 10 | 11 | 38 | 111 | 5 | 28 | 29 | 116 |
| S3_bot | 117 | 65 | 99 | 8 | 25 | 28 | ## | 32 | 14 | 8 | 25 | 65 | 92 | 8 | 23 | 27 | 37 | 36 | 5 | 9 | 12 | 111 | 99 | 14 | 25 | 28 | 112 |
| S3 | 120 | 2 | 140 | 0 | 53 | 53 | 38 | 145 | 7 | 55 | 56 | 5 | 130 | 1 | 49 | 49 | 22 | 134 | 4 | 51 | 51 | 38 | 145 | 7 | 55 | 56 | 148 |
| S7_top | 117 | 0 | 68 | 0 | 17 | 17 | 46 | 61 | 6 | 15 | 18 | 12 | 76 | 2 | 19 | 19 | 25 | 61 | 3 | 15 | 16 | 46 | 76 | 6 | 19 | 19 | 76 |
| S7_mid | 117 | 1 | 60 | 0 | 15 | 15 | 20 | 75 | 2 | 19 | 19 | 1 | 71 | 0 | 18 | 18 | 10 | 63 | 1 | 16 | 16 | 20 | 75 | 2 | 19 | 19 | 76 |
| S7_bot | 117 | 58 | 33 | 7 | 8 | 15 | 49 | 65 | 6 | 16 | 19 | 65 | 37 | 8 | 9 | 17 | 51 | 45 | 6 | 11 | 16 | 65 | 65 | 8 | 16 | 19 | 76 |
| S9(p27)_bot | 117 | 74 | 268 | 9 | 67 | 69 | 10 | 24 | 1 | 6 | 6 | 68 | 254 | 9 | 63 | 65 | 26 | 100 | 3 | 25 | 26 | 74 | 268 | 9 | 67 | 69 | 277 |
| S9(p27)_top | 117 | 74 | 116 | 9 | 29 | 33 | 10 | 50 | 1 | 12 | 13 | 68 | 89 | 9 | 22 | 27 | 26 | 20 | 3 | 5 | 8 | 74 | 116 | 9 | 29 | 33 | 133 |
| S9(p30) | 117 | 117 | 202 | 15 | 50 | 56 | 5 | 12 | 1 | 3 | 3 | 97 | 169 | 12 | 42 | 47 | 48 | 80 | 6 | 20 | 22 | 117 | 202 | 15 | 50 | 56 | 225 |
| S9(p24a,24b) | 117 | 67 | 40 | 8 | 10 | 18 | 1 | 23 | 0 | 6 | 6 | 55 | 31 | 7 | 8 | 14 | 28 | 20 | 4 | 5 | 8 | 67 | 40 | 8 | 10 | 18 | 72 |

- Extensive output from global model for post-processing
- Forces, moments, main stresses in supports' critical locations
- Forces, moments on bolted interfaces re-calculated in semi-automated way into the bolts direct stresses
- Torque on the bus/clamp bond post-processed

# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Problem Description




Current carrying and conducting elements



Global EM FE model

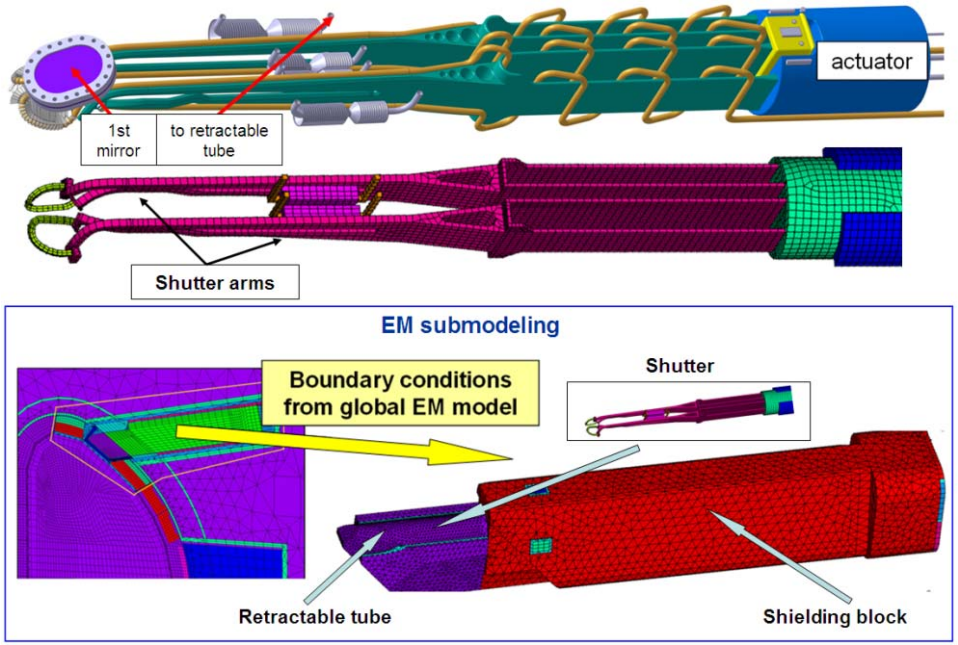
Fly in amber

- Simulation of components in an ITER diagnostic port plug to combine loading from different sources including electromagnetic transients
- Electromagnetic model combines electrically conducting parts and contacts as well as air elements
- Filling air gaps of structural parts and applying far field boundary condition is challenging

Approaches starting from global simplified electromagnetic model:

- Force transfer to detailed structural model
- Analytic electromagnetic sub modelling
- Numerical  electromagnetic sub modelling omitting air elements in order to allow for detailed component model

# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Sub-modeling

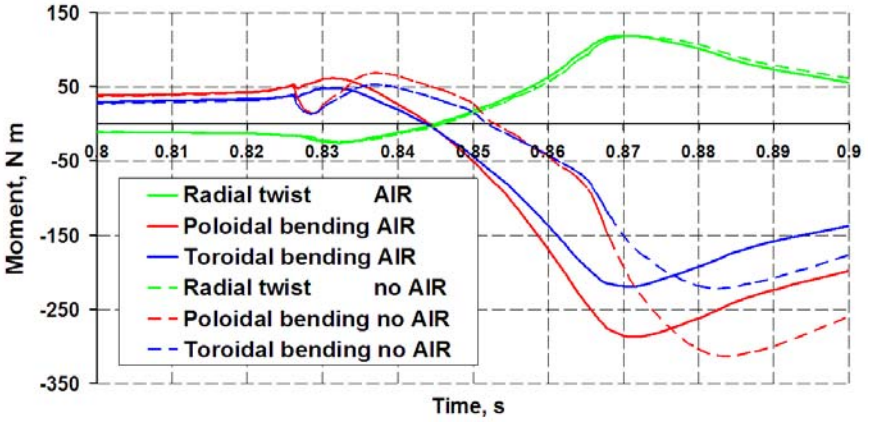



Separate EM analysis, simplified model

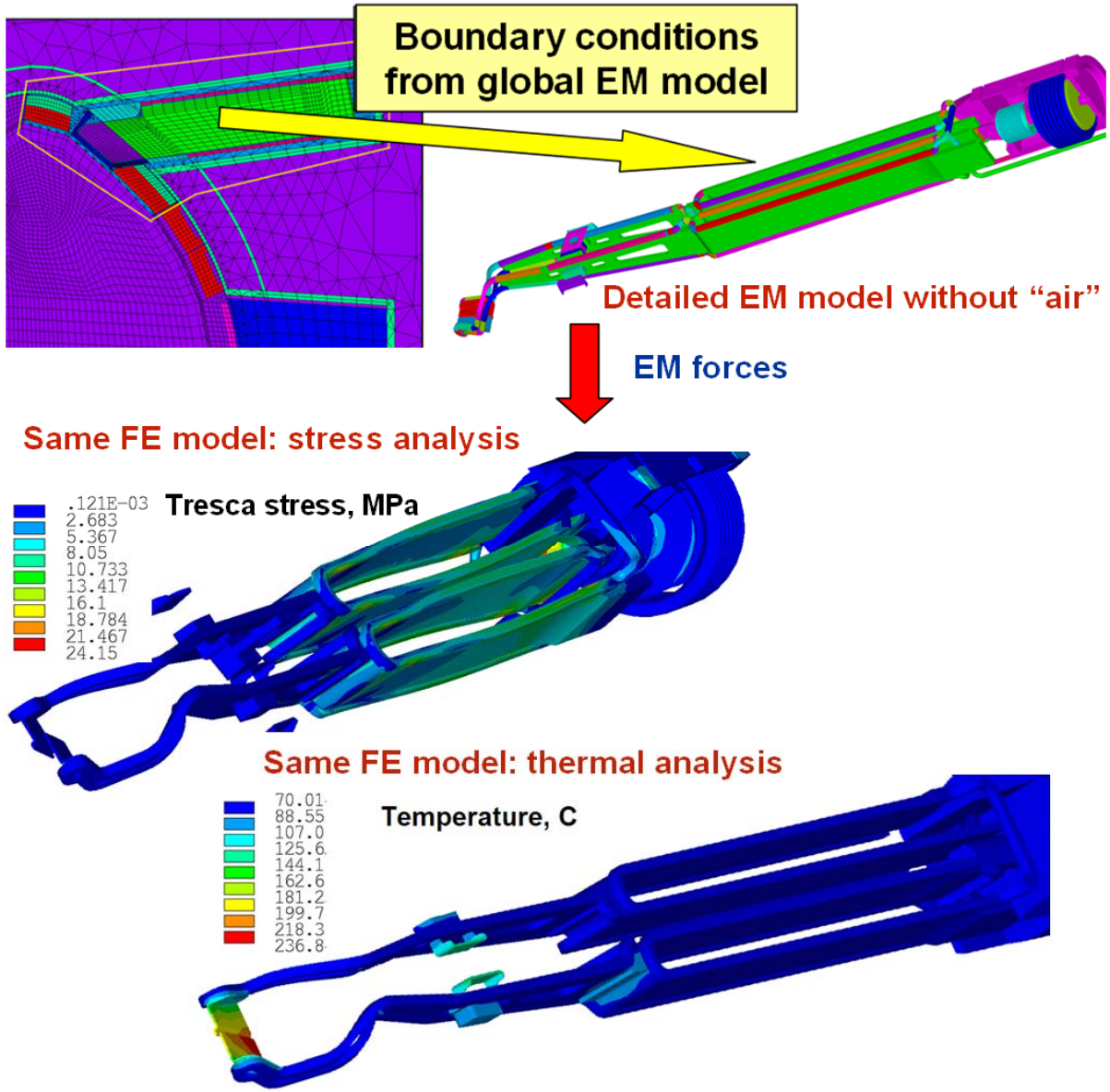
- Local model of shield block and inner components with air elements between multiple conducting parts
- Shutter geometry drastically simplified, electrical connections carefully modeled
- Boundary conditions for outer nodes derived from global model

EM analysis w/o air elements

- Analysis repeated without air elements
- Effect of eddy currents on total field negligible (skin depth criterion)
- Sufficient accuracy even without air elements

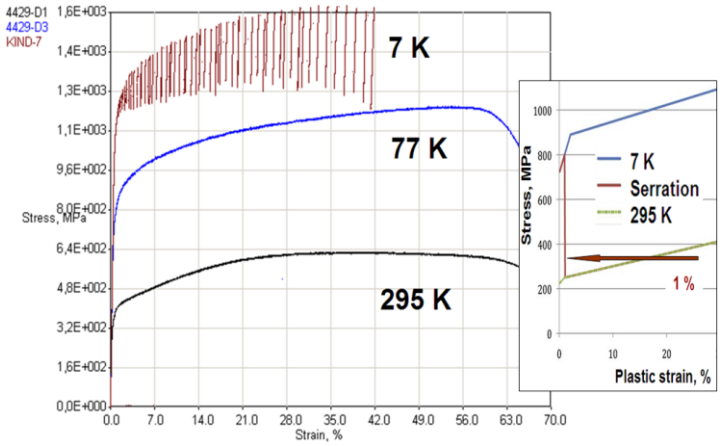


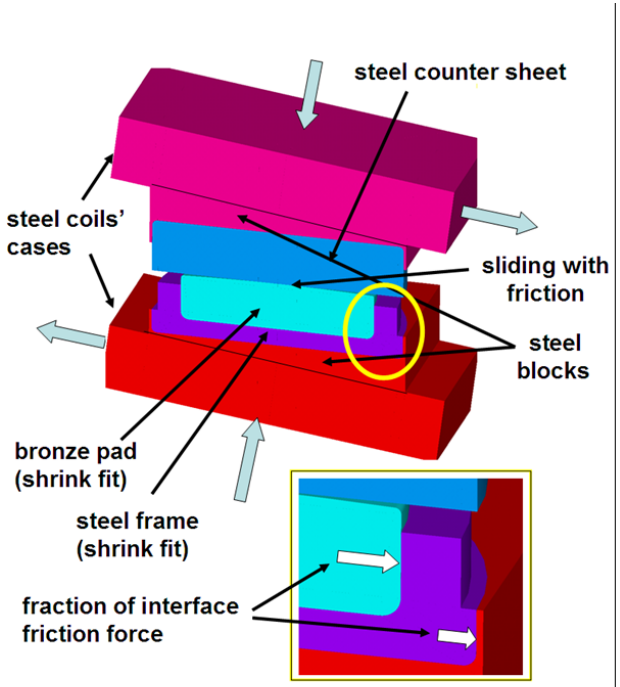
# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Multifield Model

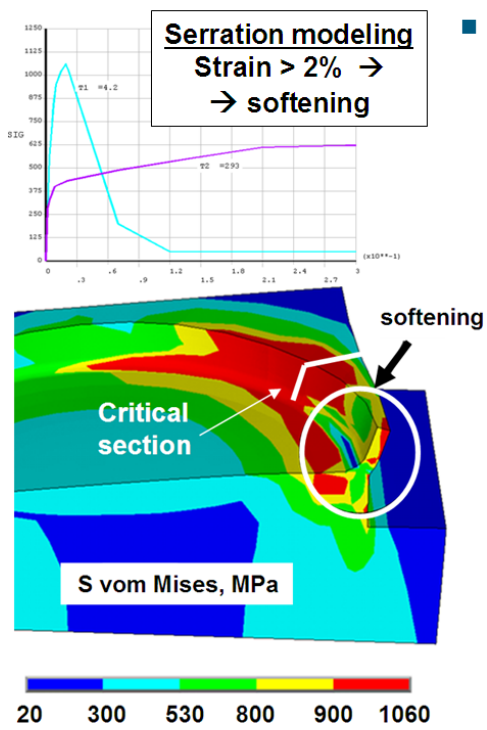



- Simplified model suited for concept iteration but not for detailed analysis
- Validation of electromagnetic analysis without air elements allows for multifield analysis of shutter arms using detailed model fitting all analysis types

# Engineering Material Model for Serration Effect W7-X Magnet System – Problem Description




- Cryogenic steel to operate in elastic range accounting for serration effect at cryogenic temperatures
- Narrow supports of W7-X magnet system work outside elastic range
- Development of approach
  - Elasto-plastic analysis with no load carried above 2% strain found out critical cross-section
  - Limit analysis with serration effect assuming step change of material behavior from 7K to room temperature above 1% strain found limiting load

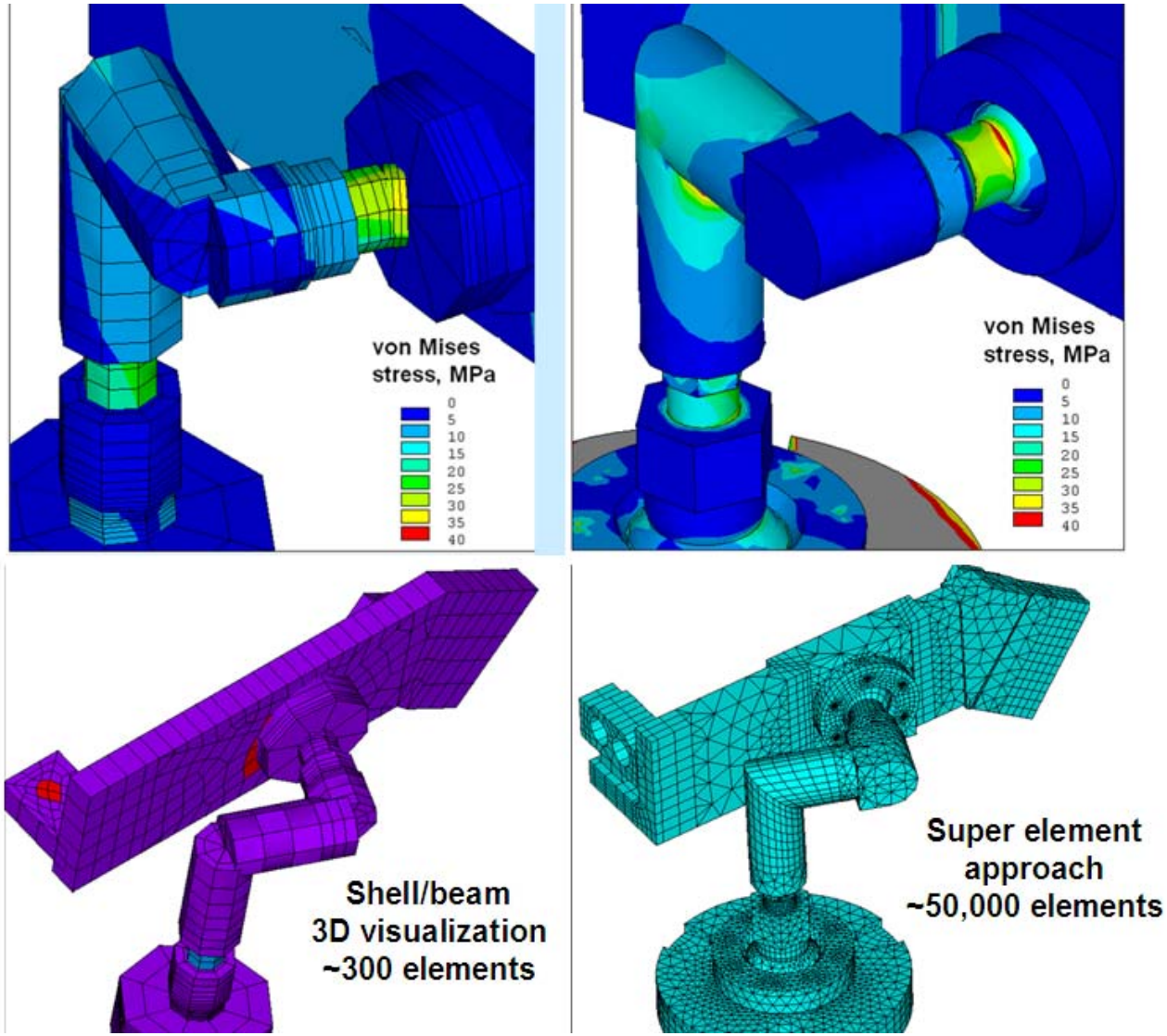
# Conclusions

Numerical models

- To be built up with clear understanding of the analysis goals and expected results,
- To be reasonably simplified, flexible for changes,
- To use 2D, axisymmetric, or beam-shell modeling whenever appropriate,
- Should be parametric for maximum modification flexibility,
- Should find tradeoff between simulation time and precision in case of time consuming dynamic analyses.

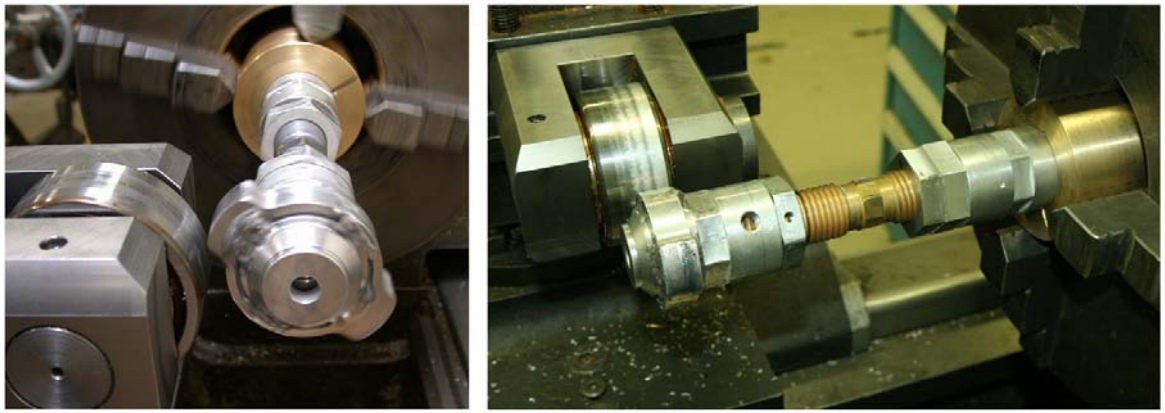
Only the finally selected design option to be checked in detail, desirably both by analysis and test.

# Simplified Beam/shell Approach
# Busbar System for W7-X – Local FE Models

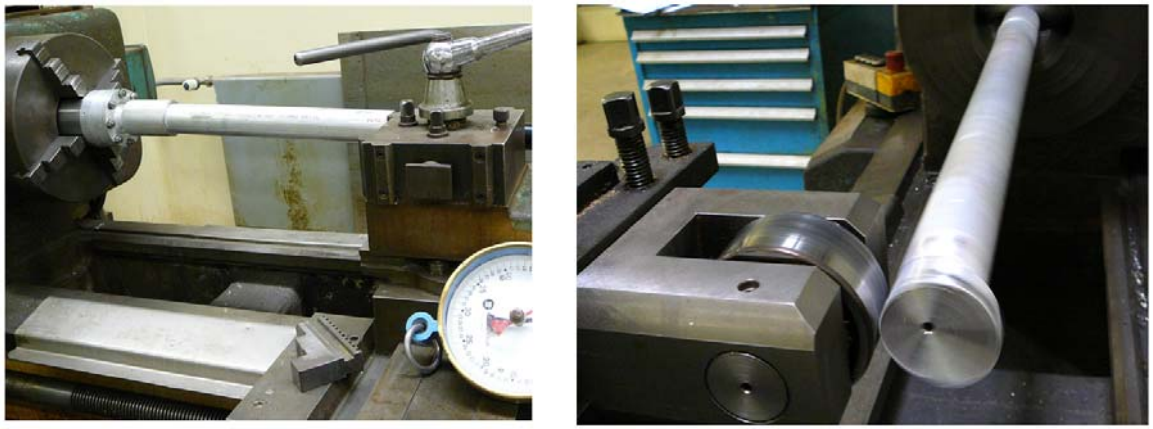



- Simplified models of critical supports validated against 3D detailed ones
- Stiffness and main stresses of both models agree well
- Simplified models directly supply forces and moments for further submodeling of critical connections or for mechanical tests

# Simplified Beam/shell Approach
# Busbar System for W7-X – Testing



Cyclic bending test of aluminum threaded connection at RT

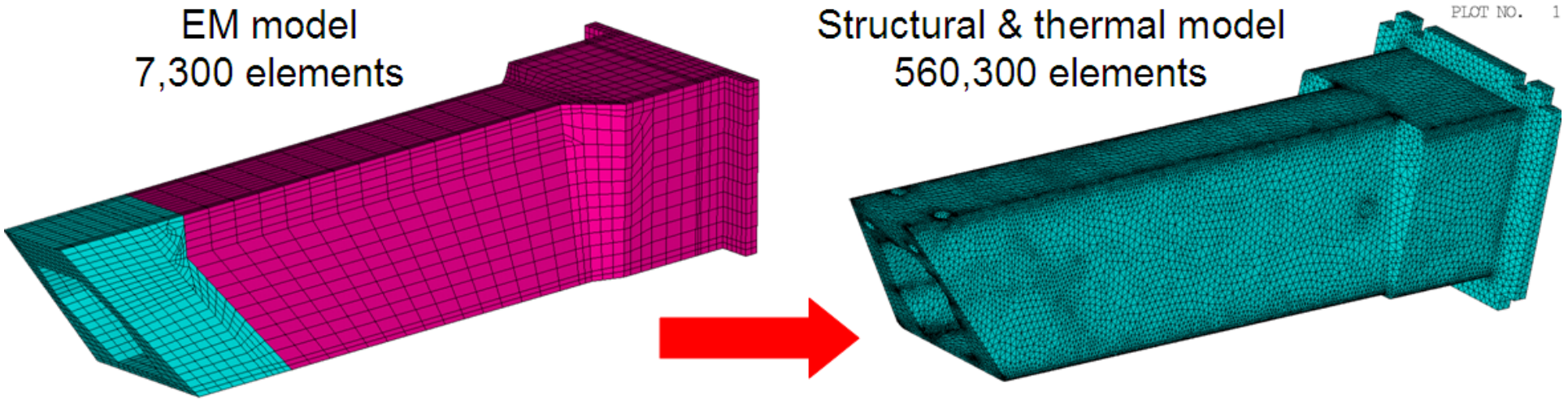


Cyclic bending test of aluminum weld at RT

- Cyclic bending of aluminum threaded connection and aluminum weld

- Busbar bending – non-insulated versus insulated
- Wearing of busbar insulation in the clamps/supports – sliding with compression
- Busbar insulation – compression, tension, shearing
- Clamp – torque taken by glued connection
- Bolts – required torque to create bolt preload, loss of preload, cyclic loading etc.
- Spherical hinges of the supports under applied moment – RT and 77 K

# Multifield Analysis Including Electromagnetic ITER Diagnostic Port Plug – Load Transfer




Models having different mesh and even slightly different geometry

- External code seeking for each “loaded” node of the source model the geometrically nearest nodes of the target model implying
  - A sound choice of an epsilon neighborhood for target nodes
  - Reliable checks of calculated global and local moments on the structure